

Nuclear dependence of the transverse-single-spin asymmetry for forward neutron production in polarized $p+A$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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During 2015 the Relativistic Heavy Ion Collider (RHIC) provided collisions of transversely polarized protons with Au and Al nuclei for the first time, enabling the exploration of transverse-single-spin asymmetries with heavy nuclei. Large single-spin asymmetries in very forward neutron production have been previously observed in transversely polarized $p+p$ collisions at RHIC, and the existing theoretical framework that was successful in describing the single-spin asymmetry in $p+p$ collisions predicts only a moderate atomic-mass-number (A) dependence. In contrast, the asymmetries observed at RHIC in $p+A$ collisions showed a surprisingly strong A dependence in inclusive forward neutron production. The observed asymmetry in $p+Al$ collisions is much smaller, while the asymmetry in $p+Au$ collisions is a factor of three larger in absolute value and of opposite sign. The interplay of different neutron production mechanisms is discussed as a possible explanation of the observed A dependence.

Understanding forward particle production in high energy hadron collisions is of great importance, because most of the energy goes in the forward direction, and therefore informs our understanding of overall particle production. This has particular importance in studies at colliders and of ultra-high energy cosmic rays, where the interpretation, including possibly beyond the standard model, requires estimation through modeling of forward particle production [1, 2]. Mechanisms for forward particle production are not well understood, as perturbative quantum chromodynamics (pQCD) is not applicable at small momentum transfers and diffractive production mechanisms are not well modeled. To better understand production mechanisms, measurement of the single spin asymmetry A_N , describing the azimuthal asymmetry of particle production relative to the spin direction of the transversely polarized beam or target provides crucial tests and deeper insight beyond just cross-section measurements. The spin degree of freedom has served as a strong discriminator between theoretical models. For example, the origin of the large asymmetries discovered in forward meson production in $p+p$ collisions from $\sqrt{s}=4.9\text{--}19.4$ GeV [3–10] and later confirmed at $\sqrt{s}=62.4\text{--}500$ GeV at the Relativistic Heavy Ion Collider (RHIC) [11–16] has been under intensive discussion for three decades and still remains an open question [17]. Despite substantial theoretical attempts to reproduce data in the pQCD regime using the conventional $2 \rightarrow 2$ parton scattering processes, the latest multiplicity dependent A_N measurements from RHIC [18] indicate that a significant contribution to the asymmetry may be of a diffractive nature.

In the case of neutron production in $p+p$ collisions, production cross sections [19–21] were successfully explained in terms of one-pion exchange [22–26]. However, that alone could not explain the sizable A_N in very forward (near zero degree) neutron production, discovered at RHIC in $p+p$ collisions at $\sqrt{s}=200$ GeV [21]. To reproduce the experimental asymmetry, an interference between the spin-flip π exchange and a non spin-flip a_1 -Reggeon exchange was necessary [26]. Kopeliovich, Potashnikova, and Schmidt considered nuclear absorption effects as a source for a possible A dependence of A_N , and found only a small effect [27].

In this Letter, we report the first measurements in 2015 of A_N for very forward neutron production in collisions between polarized protons and nuclei (Al and Au) at $\sqrt{s_{NN}}=200$ GeV with the PHENIX detector [28]. The average beam polarization in $p+p$, $p+Al$, and $p+Au$ data samples was 0.515 ± 0.002 , 0.59 ± 0.02 and 0.59 ± 0.04 , respectively, with additional global uncertainty of 3% from the polarization normalization [29, 30].

The experimental setup using a zero-degree calorimeter (ZDC) [31] and a position-sensitive shower-maximum detector (SMD) is similar to the one used for $p+p$ data [32]. The ZDC comprises three modules located in series at ± 18 m away from the collision point. The ZDC has an acceptance in the transverse plane of 10×10 cm², with a total of 5.1 nuclear interaction lengths (or 149 radiation lengths), and an energy resolution of $\sim 25\text{--}20\%$ for 50–100 GeV neutrons. The SMD comprises x - y (horizontal-vertical) scintillator strip hodoscopes inserted between the first and second ZDC modules (approximately at the position of the maximum hadronic shower), and provides a position resolution of ~ 1 cm for 50–100 GeV neutrons. These detectors are located downstream of the RHIC DX beam splitting magnet, so that near beam-momentum charged particles from collisions are expected to be swept into the beam lines and out of the ZDC acceptance (see Fig. 1).

To accommodate asymmetric $p+A$ collisions of beams with different rigidity, the DX magnets were moved horizontally [33]. In this special setup for the present measurement, the proton beam was angled off axis by ~ 2 mrad relative to the nominal beam direction at the collision point, with a crossing angle with the Au (Al) beam of 2.0 mrad (1.1 mrad). Correspondingly, the ZDC was moved by 3.6 cm (2 mrad) to keep zero-degree neutrons at the ZDC center (see Fig. 1).

The data was collected with triggers employing the ZDC and beam-beam counters (BBCs) [34]. Only the north ZDC detector, facing the incoming polarized proton beam was used in this analysis. Two BBC counters are located at ± 144 cm from the nominal collision point along the beam pipe and are designed to detect charged particles in the pseudorapidity range of $\pm(3.0\text{--}3.9)$ with full azimuthal coverage. The ZDC inclusive trigger required the energy deposited in the ZDC to be

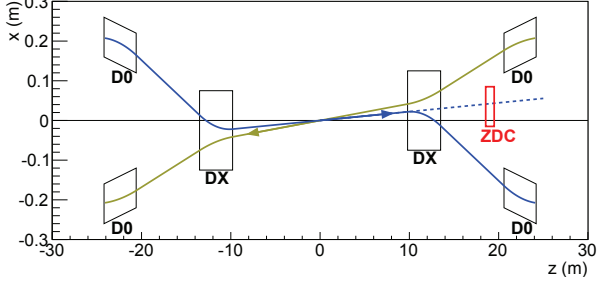


FIG. 1. ZDC location and beam orbits of proton (blue) beam and heavy-ion (yellow) beam in the special stores used for this analysis; the z -axis shows the nominal beam direction, and the dashed line represents the zero-degree neutron trajectory. DX and D0 are the RHIC beam bending dipole magnets.

greater than 15 GeV. The ZDC \otimes BBC-tag trigger in addition required at least one hit in each of the BBCs, and ZDC \otimes BBC-veto trigger required no hits in both BBCs. The latter two sets represent mutually exclusive but not complete subsets of the ZDC inclusive triggered data.

As described in detail in Ref. [32], event selection and neutron identification cuts include: (1) a total ZDC energy cut of 40–120 GeV; (2) at least two SMD strips fired (above threshold) in both x and y directions, and a nonzero (above threshold) energy in the second ZDC module (to reject photons); and (3) an acceptance cut of $0.5 < r < 4.0$ cm for the reconstructed radial distance r from the determined beam center (to reduce the impact of the position resolution and edge effects in the asymmetry measurements).

The raw asymmetry ($\epsilon_N(\phi)$) is calculated using the square-root formula [32] for each azimuthal angle (ϕ) bin. The polarization normalized A_N^{fit} is then extracted from the fit to a sine function

$$\epsilon_N(\phi) = P A_N^{\text{fit}} \sin(\phi - \phi_0), \quad (1)$$

where P is the proton beam polarization and ϕ_0 is the polarization direction in the transverse plane.

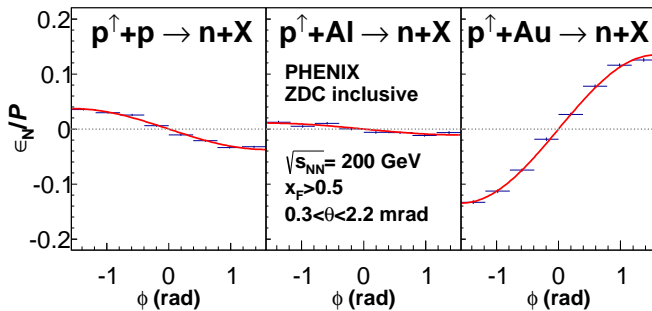


FIG. 2. A_N^{fit} fit of ZDC inclusive samples.

Figure 2 compares $\epsilon_N(\phi)/P$ results for ZDC inclusive samples from $p+p$, $p+Al$ and $p+Au$ collisions and shows

the nuclear dependence of A_N^{fit} , including a sign change from negative in $p+p$ collisions to positive in $p+Au$ collisions. The obtained A_N^{fit} is then corrected for backgrounds and detector responses. The main background contribution comes from protons, generated by elastic, diffractive, and hard processes.

Protons from elastic and diffractive reactions travel close to the beam line and are swept by the DX magnet to the right (toward negative x in Fig. 1). Only a small fraction of such protons scattered by large angles, larger than 4–5 mrad, fall in the ZDC acceptance. Because the cross section for these reactions falls sharply with scattering angle, these protons contribute mainly on the right side of the ZDC. This contribution was evaluated from the particle position distribution as measured by the SMD and found to be 9% and 32% in the inclusive ZDC and ZDC \otimes BBC-veto triggered samples respectively in $p+p$ collisions, $< 2\%$ in both samples in $p+A$ collisions, and negligible in ZDC \otimes BBC-tag samples of both $p+p$ and $p+A$ collisions. The significant suppression of elastic and diffractive proton background relative to the neutron signal in $p+A$ collisions can be understood as due to the stronger magnetic fields in the DX magnets. Correspondingly, the minimum scattering angle for the elastic and diffractive proton backgrounds to reach the ZDC acceptance increases from 3.8 mrad to 5 mrad, leading to a cross section reduction by an order of magnitude.

The contribution of charged hadron background from hard scattering processes, distributed nearly uniformly over the ZDC acceptance, was estimated using PYTHIA6 [35] with a GEANT3 [36] detector simulation. However, from previous studies where a charge veto counter was installed in front of the ZDC to measure the charged hadron background, it was found that simulation underestimates the proton background by a factor of ~ 2 [32]. Therefore the hard scattering background contribution from simulation was scaled by a factor of two with an uncertainty equal to the size of the increase. In $p+p$ collisions this background fraction resulted in $6 \pm 3\%$, $3 \pm 1.5\%$ and $12 \pm 6\%$ in ZDC, ZDC \otimes BBC-veto and ZDC \otimes BBC-tag triggered samples, respectively. In $p+A$ collisions due to increased neutron signal from electromagnetic (EM) processes (to be discussed later), the relative background contributions are expected to be smaller. Therefore the measured asymmetries in $p+A$ collisions were not corrected for background, but one side systematic uncertainties (in the direction of asymmetry dilution) equal to background fraction plus 1σ uncertainty in the $p+p$ case, i.e. 9%, 4.5% and 18% were conservatively assigned in ZDC, ZDC \otimes BBC-veto and ZDC \otimes BBC-tag triggered samples, respectively.

From the considerations above, only the $p+p$ asymme-

tries were corrected for backgrounds according to

$$A_N^S = \frac{A_N^{\text{fit}} - r_{\text{eff}} A_N^B}{1 - r_{\text{eff}}}, \quad (2)$$

where A_N^S and A_N^B stand for signal and background asymmetries, and r_{eff} is the “effective” background fraction in the reconstructed neutron sample. The parameter r_{eff} accounts for the dilution of the background effect in A_N^{fit} in the case when the background contributes preferably on one side of the detector (as from elastic or diffractive protons). The background asymmetry A_N^B was evaluated from the comparison of asymmetries with and without the charge veto cut from the 2008 data when the charge veto counter was available. The asymmetries A_N^B were found to be consistent with zero within statistical uncertainties for all triggers. After background correction, A_N^S results for $p+p$ from 2008 and 2015 data were found to be consistent within statistical uncertainties. Asymmetries from 2015 data were used in the final results.

Besides charged hadrons, the other background sources are photons and K^0 mesons. From PYTHIA6 simulation their contribution after the analysis cuts was evaluated to be below 3% in all collision systems and triggers, and was neglected in the asymmetry results.

The measured asymmetries are affected by detector resolutions and other detector systematic effects (e.g. edge effects), as well as by the uncertainty in the shape of the neutron production cross section vs p_T and x_F , and the assumption for the shape of $A_N(p_T)$ within the p_T range sampled in this analysis. These effects were studied in detail with a GEANT3 Monte Carlo simulation. The fully corrected transverse single spin asymmetry A_N was calculated as $A_N = A_N^S/C_\phi$ where the correction factor C_ϕ was calculated in the simulation as the ratio of the measured asymmetry to the average input asymmetry over the neutron sample collected with experimental cuts used in the analysis. The biggest variation in C_ϕ comes from the position resolution uncertainty and the assumption for $A_N(p_T)$. The position resolution in the simulation was varied by changing noise and thresholds in the SMD channels, as well as by introducing a cross talk effect, similar to [32]. An overall value of 3% was assigned to the C_ϕ uncertainty. For the shape of $A_N(p_T)$, it was modeled as $A_N(p_T) = \text{const}$ (as was assumed in [32]) and $A_N(p_T) \propto p_T$ (which is supported by theory [26]). The difference of 3% was included in the C_ϕ uncertainty. The final correction factor applied to the measured asymmetries is $C_\phi = 0.855 \pm 0.036$.

The analyzed data correspond to the neutron sampled p_T in the range smaller than 0.25 GeV/c peaked at about 0.1 GeV/c, which is affected by detector resolutions. Due to the varying contribution of different processes to neutron production, the sampled p_T distribution may vary in different collision systems and in different triggered data. Figure 3 shows the differences in the radial distributions, which is related to the neutron production

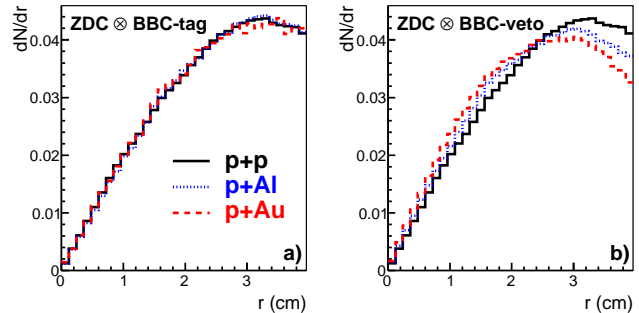


FIG. 3. The r distribution of (a) ZDC⊗BBC-tag sample and (b) ZDC⊗BBC-veto sample for three collision systems.

cross section $d\sigma/dp_T$ by $p_T \propto r$ [32]. From a comparison with simulation assuming different slope parameter, b , in the parameterization $d\sigma/dp_T \sim e^{-b \cdot p_T}$, the data were found to be consistent with $b = 4$ (GeV/c) $^{-1}$ for all collision systems in ZDC⊗BBC-tag triggered data, and $b = 4, 6$ and 8 (GeV/c) $^{-1}$ in $p+p$, $p+Al$ and $p+Au$ collisions, respectively, in ZDC⊗BBC-veto triggered sample, with uncertainty $\sigma_b = 1$ (GeV/c) $^{-1}$ reflecting its sensitivity to SMD gain calibration and thresholds. These variations lead to a difference in the average p_T sampled in different collision systems and triggers by as much as 10%.

Figure 4 and Table I summarize the results for A_N in forward neutron production in $p+p$, $p+Al$ and $p+Au$ collisions, for ZDC inclusive, ZDC⊗BBC-tag and ZDC⊗BBC-veto samples. In addition to the beam polarization, background, and smearing correction (C_ϕ) discussed above, the other sources of systematic uncertainties are the ZDC and SMD gain calibrations (including SMD threshold variation) and location of the beam center on the SMD plane.

From Fig. 4, the A dependence of A_N for inclusive neutrons is strong. Compared to the A_N of $p+p$ collisions, the observed asymmetry in $p+Al$ collisions is much smaller, while the asymmetry in $p+Au$ collisions is a factor of three larger in absolute value and of opposite sign. This behavior is unexpected because the theoretical framework using π and a_1 -Reggeon interference can only predict a moderate nuclear dependence, and there is no known mechanism to flip the sign of A_N within this framework [27].

The asymmetries requiring BBC hits are remarkably different. Once BBC hits are required (ZDC⊗BBC-tag), the drastic behavior of the inclusive A_N vanishes and its sign stays negative, approaching $A_N = 0$ at large A . In contrast, the strong A dependence is amplified once no hits in the BBC are required (ZDC⊗BBC-veto). While the BBCs cover a limited acceptance, the requirement (or veto) of hits in the BBC should place constraints on the activity near the detected neutron and thus the corresponding production mechanism.

TABLE I. A_N for forward neutron production in $p+p$, $p+Al$, and $p+Au$ collisions, for ZDC inclusive, ZDC \otimes BBC-tag, and ZDC \otimes BBC-veto samples.

	Inclusive	$p+p$ BBC Tag	BBC Veto	Inclusive	$p+Al$ BBC Tag	BBC Veto	Inclusive	$p+Au$ BBC Tag	BBC Veto
A_N	-0.0540	-0.0641	-0.0309	-0.0126	-0.0566	0.0727	0.1574	-0.0150	0.2342
Statistical error	± 0.0012	± 0.0019	± 0.0035	± 0.0015	± 0.0026	± 0.0027	± 0.0019	± 0.0053	± 0.0024
Systematic error:									
Background	± 0.0069	± 0.0091	± 0.0170	± 0.0012	± 0.0102	-0.0036	-0.0145	± 0.0027	-0.0115
Smearing	± 0.0023	± 0.0027	± 0.0013	± 0.0005	± 0.0024	± 0.0031	± 0.0066	± 0.0006	± 0.0099
Beam pos.	± 0.0086	± 0.0062	± 0.0097	± 0.0040	± 0.0038	± 0.0060	± 0.0023	± 0.0036	± 0.0084
Polarization	± 0.0004	± 0.0005	± 0.0007	± 0.0005	± 0.0022	± 0.0028	± 0.0112	± 0.0012	± 0.0168
Calibration	± 0.0027	± 0.0010	± 0.0067	± 0.0012	± 0.0042	± 0.0042	± 0.0042	± 0.0085	± 0.0062
Total systematic	± 0.0116	± 0.0114	± 0.0208	± 0.0044 -0.0043	± 0.0121 -0.0065	± 0.0084 -0.0091	± 0.0139 -0.0201	± 0.0097 -0.0094	± 0.0221 -0.0249

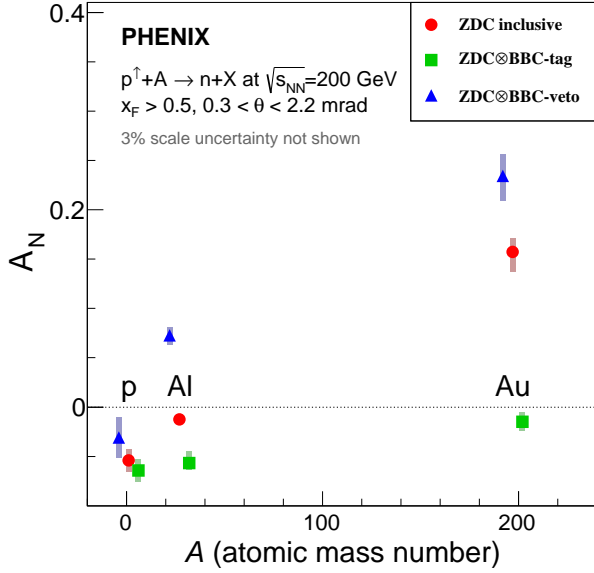


FIG. 4. Forward neutron A_N in $p+A$ collisions for $A=1$ (p), 27 (Al) and 197 (Au), for ZDC inclusive, ZDC \otimes BBC-tag and ZDC \otimes BBC-veto triggered samples; color bars are systematic uncertainties, statistical uncertainties are smaller than the marker size. Data points are shifted horizontally for better visibility.

One possibility to explain the present results is a contribution from EM interactions, which have been demonstrated to be important for reactions with small momentum transfer, e.g., in ultra-peripheral heavy ion collision at RHIC [37–40] and Large Hadron Collider [41–44], including forward neutron production in $p+A$ collisions [45], and polarization observables in fixed target experiments [46, 47]. Although it was ignored in the interpretation for the $p+p$ data [27], EM interactions become increasingly important for large atomic number (Z) nuclei, as the EM field of the nucleus is a rich source of virtual photons, increasing as Z^2 . Forward neutrons in the final state can be produced through nonresonant photo- π^+ production and neutron decay channel from photo-nucleon excitation processes, such as the Δ resonance.

According to a Monte-Carlo study [45], the neutron and its associated π^+ produced through this process are substantially boosted towards the proton beam direction, so that only a small fraction of pions would be detected by the BBC. Thus, a large fraction of EM processes are expected to be suppressed in the ZDC \otimes BBC-tag events while enhanced in the ZDC \otimes BBC-veto events. Here, it is noted that the importance of EM processes in $p+A$ collisions is also hinted at in the present data: the ratio between reconstructed neutrons in ZDC \otimes BBC-veto and ZDC \otimes BBC-tag samples increases from smaller than 0.5 in $p+p$ to ~ 1 (~ 5) in $p+Al$ ($p+Au$) collisions. In addition, a faster drop of the neutron production cross section with p_T in $p+A$ collisions in ZDC \otimes BBC-veto triggered data discussed in Fig. 3b is consistent with increasing role of EM processes that have softer p_T distribution than hadronic processes.

Similarly in the asymmetry measurements, contributions of different production mechanisms may be suppressed or enhanced by different event selection triggers. Hence, while the result for the ZDC \otimes BBC-tag sample may be explained by the conventional pion and a_1 -Reggeon interference mechanism [27], that for the ZDC \otimes BBC-veto triggered sample could be explained by contributions from interference with EM amplitudes which are expected to be enhanced in that dataset. However, the strengths of these interference contributions are not known, and there could be other mechanisms, such as diffractive scattering, which is also expected to be enhanced by a ZDC \otimes BBC-veto trigger. Therefore, further studies are needed to fully understand the present results.

In summary, we observe an unexpectedly strong A dependence in A_N of inclusive forward neutron production in polarized $p+A$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Furthermore, a distinctly different behavior of A_N was observed in two oppositely trigger-enhanced data sets. These surprising behaviors could be explained by a contribution of EM interactions, which may be sizable for heavy nuclei. Further studies of the production mechanism including EM contributions and diffractive scattering would have an impact not only to hadron physics, but also to cosmic-ray science, where measurements of high-energy cosmic rays depend on models of forward particle

production in the interactions with nuclei in the air.

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